Measured and Calculated Performance of a High Frequency, 4 K Stage, He-3 Regenerator

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ABSTRACT

Efficiencies of small 4 K cryocoolers are less than 1% of Carnot, whereas 80 K cryocoolers achieve efficiencies of up to almost 20% of Carnot. The primary loss mechanisms in low temperature regenerative cryocoolers are caused by the non-ideal gas properties of the He-4 working fluid and the reduced volumetric heat capacity of the regenerator matrix compared with that of He-4 at these low temperatures. A recently developed model, REGEN3.3, which incorporates the thermodynamic and transport properties of He-3, shows that using He-3 should improve the performance of 4 K regenerators considerably. REGEN3.3 was used to design an optimized test apparatus to measure the performance of a He-3, 4 K regenerator with the warm end precooled by a Gifford-McMahon cryocooler to about 35 K. The test regenerator is designed to operate at 30 Hz and uses a layered matrix of gadolinium oxysulphate (GOS) spheres at the cold end and erbium-praseodymium (ErPr) spheres at the warm end. The experimental test apparatus, testing procedures and the results are presented. In addition, a novel method to improve the phase shifting at the warm end of the small He-3 cold-stage pulse tube is described along with its impact on the cycle performance.

INTRODUCTION AND SCIENTIFIC BACKGROUND

A clear gap exists between the continued rapid development and miniaturization of low-temperature applications and the availability of applicable cryogenic refrigeration systems. Expeditious insertion of new cold technologies into new devices, such as superconducting electronics and wireless applications, commercial and medical imagery, infrared imaging and space applications is hinged on the ability to provide reliable and efficient low temperature cryogenic cooling. Even though there have been considerable recent advances in improving the cooling capabilities of the cryocoolers used for these applications, such as the pulse tube cryocooler, this type of regenerative cryocooler can still be significantly improved with respect to its efficiency at low temperatures. Typically for low temperature applications, the cryocoolers used have been either Gifford McMahon (GM) cryocoolers or GM-type pulse tube cryocoolers that operate at frequencies of about 1 Hz. The efficiency of these cryocoolers is only in the range of 0.5 to 1.0 % of Carnot, whereas warmer 80 K cryocoolers are considerably more efficient; often achieving efficiencies of at least 15 % of Carnot. The low efficiency of 4 K cryocoolers leads to large compressors with large input powers. The low operating frequency of the GM and GM-type pulse tube also leads to large temperature

Cryocoolers 16, edited by S.D. Miller and R.G. Ross, Jr.

oscillations at the cold end at operating frequency of the cryocooler as well as vibration export. The amplitude of the temperature oscillation decreases as the cryocooler operating frequency increases. Transitioning to higher frequencies would allow the use of Stirling cryocoolers or Stirling-type pulse tube cryocoolers, which have much higher efficiencies in converting electrical power to usable acoustic power. These frequencies are typically in the range of 30 to 60 Hz. These higher frequencies generally lead to even greater losses in the regenerator. The principal loss mechanism in the low temperature regenerator originate in the non-ideal gas properties of the He-4 working fluid, and in the reduced volumetric heat capacity of the regenerator matrix compared with that of He-4 at these low temperatures. Recent work with a 4 K GM-type pulse tube and a Stirling-type pulse tube cryocooler[1,2,3] has shown that the use of He-3 instead of He-4 increased the cooling power for the same power input in these types of cryocoolers. To better understand this phenomenon some initial modeling has been done which clearly shows that the thermodynamic characteristics of He-3 are much better matched for use with the low temperature regenerator matrix materials. Figure 1 shows the volumetric heat capacity of some of the low temperature regenerator materials investigated compared with that of He-4 and He-3 at various pressures. He-3 exhibits lower volumetric heat capacity than He-4 and is better matched to work with the lower heat capacities of the matrix materials. By formulating an analytical model that incorporates these real gas properties into an efficiency term for the regenerator, we can calculate the expected efficiency for a regenerator with any given matrix material and working gas. Numerical regenerator modeling software, which incorporates previous work in He-3 transport and thermodynamic properties[4, 5], was used to compute the resulting efficiency values. The results are shown in Figure 2. Here it is clearly shown that replacing the classically used He-4 gas with He-3 improves the expected efficiency of low temperature regenerators significantly. For example, the efficiency of a regenerator made of GOS + $Er_{0.5}Pr_{0.5}$ employing He-3 is about five times that of a regenerator made with ErNi using He-4. This theoretical analysis further establishes that the real gas properties of He-3 cause it to be better suited for use in low temperature regenerative cryocoolers.

This research experimentally investigates and tries to empirically verify the results from this preliminary theoretical study in order to establish an understanding of the effects of the real gas behavior of He-3 as it relates to use in low temperature regenerative heat exchangers.

RESEARCH METHODOLOGY

The overall guiding principle of this research was to significantly improve the efficiency and cooling capacity of small 4 K cryogenic coolers by means of understanding the physical phenomena and impact of real gas behavior of the oscillating helium gas at these low temperatures. Preliminary analytical models show that incorporating He-3, with appropriately matched regenerator matrix materials as described in the scientific background, can significantly improve the thermodynamic

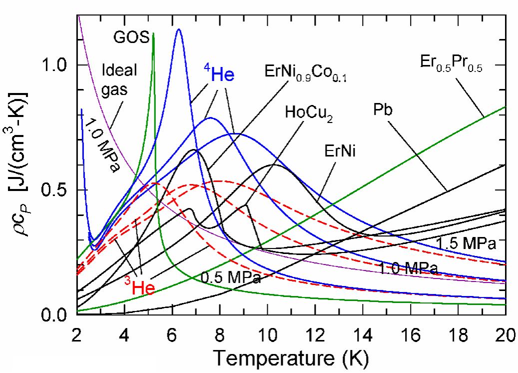

Figure 1: Volumetric heat capacity of various low temperature regenerator materials investigated here compared with that of He-4 and He-3 at various pressures - 0.5MPa, 1.0MPa, 1.5MPa.

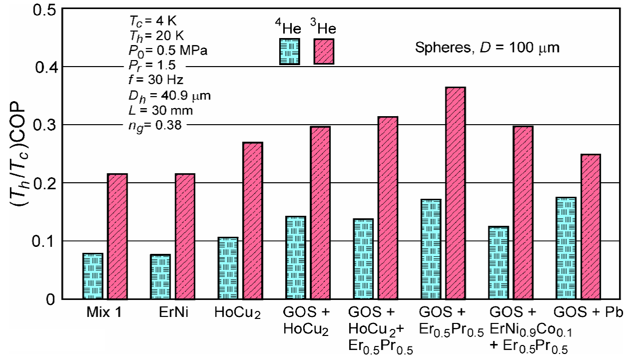

Figure 2. Regenerator efficiency for various regenerator materials using He-3 vs. He-4.

efficiency of the low temperature regenerative cycle. Empirical data is necessary to validate and improve this theoretical model and improve our understating of the thermodynamics involved when using He-3. In order to effectively perform this research, a novel test device was proposed and constructed. This testing device, as shown in Figure 3, allows for low temperature He-3 test regenerators to be tested under varying operating conditions (controllable pressure and temperature) independently of a complete cryocooler. By means of a thermally connected GM 4 K cryocooler and an attached heater at the regenerator cold heat exchanger, the temperature gradient across the regenerator can be controlled. By means of a linear compressor providing a controllable oscillating pressure wave at a controllable fill pressure, the acoustic power characteristics provided to the regenerator can be modified. Being able to control these two parameters simultaneously and independently while performing measurements on temperature, pressure and heat flow values allows us to study the real gas behavior of the He-3 and its effects on the heat transfer characteristics and efficiency of the He-3 regenerator under various real operating conditions. Figure 4 shows the completed laboratory test bench with the associated components and sensing equipment.

This research project began with the assembly of the test apparatus and calibration of the various sensors. In the device calibration there were a few caveats that should be elaborated upon. One is the pressure sensors; these are purchased pre-calibrated by the manufacturer for working at

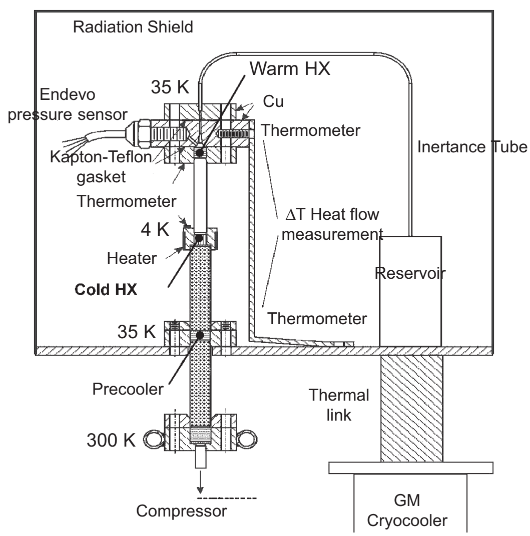

Figure 3. He-3 Regenerator Test Apparatus.

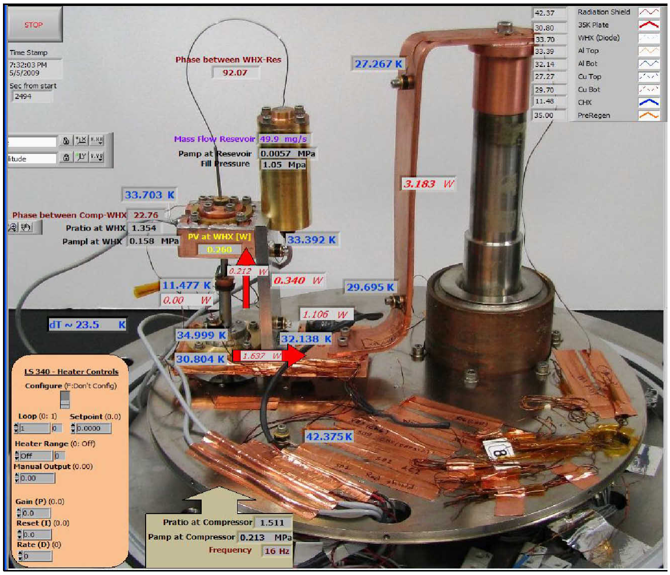

Figure 4. Laboratory test bench with associated sensors (both vacuumed radiation shields are detached).

room temperatures but must be carefully re-calibrated to work accurately down at 35 K. In addition in order to accurately determine the heat flows we first had to quantify the parasitic heat loads at the different components. This was done by measuring the heat-up rate of these examined components under increasing heat loads. The resulting curves were then extrapolated down to determine the point at which the heat-up rate would be zero: this same point then corresponded to the parasitic heat loss on this component. The results of this exercise performed on the 35 K cooling plate are shown in Figure 5. Another sensor, or actually measurement device, that needed particular attention in calibration was the heat flow sensor. There were two heat flow "measurers", one was an OFHC copper strap, and the other was a Aluminum 6061 strap, both with accurately defined cross-sectional area and measured coefficient of thermal conductivity at the required temperature of operation. To complicate matters, the conductive materials such as the copper and aluminum used in this device have a very nonlinear dependence on temperature at very low temperatures. This required doing preliminary testing on the test system to first determine the dependence of the conductivity parameter on temperature for the specific strap in place. By measuring the temperature gradient across the length of the strap during operation, we can determine the heat flow out of the regen-

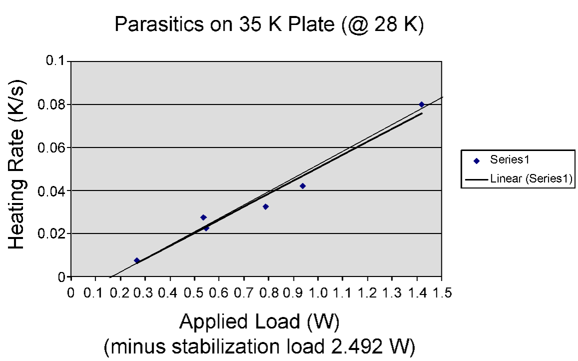

Figure 5. Calibration curve for the parasitic heat load on the 35 K plate.

erator test device on its two ends. Other more commonly available sensors such as the cryogenic temperature sensors and resistance heaters were relatively straight forward to calibrate and posed no trouble.

In general, a modular mechanical design philosophy was implemented in order to simplify the process of assembly/disassembly in the process of iterative testing. Along with the hardware setup, in order to accurately characterize and diagnose the behavior of the 4 K regenerator, a detailed user interface was programmed using National Instruments Labview software. Not only does it record all the directly measured parameters such as temperature and pressure throughout the system but it performed live derivative calculations to determine the relevant parameters such as mass flows into the regenerator and reservoir, acoustic power at the warm and cold heat exchanger, pressure ratios, phase shifts between the pressure and mass flows at various points in the system, cooling rate, and the enthalpy flow through the buffer tube. Along with these measurements the software also interfaced with a PID temperature control loop which managed the 4 K regenerator's warm and cold heat exchangers set-point temperature and cooling load.

RESULTS

Since completing the assembly of the test apparatus, the regenerator was characterized for its behavior at various operating temperatures and load conditions while using He-4 as its fluid. Along with this, the operating frequency, pressure and inertance tube length were optimized for the lowest cold point temperatures. During this process of preliminary runs and system optimization, various system defects (such as leaks, plugs, and inadequate flow transitions) were discovered and corrected.

In Figure 6 we see the output of the optimization process for the inertance tube length. Here we clearly see that the phase shifting abilities of the inertance tube and reservoir are entirely inadequate providing only +40 deg of phase shifting (an optimized inertance tube should provide -30 deg and an orifice alone can provide 0 deg). This inability to provide phase shifting is primarily attributed to the low levels of acoustic power at the entrance to the inertance tube, a parameter that has previously been shown to significantly affect the performance of inertance tubes. As a result, various different approaches were made to improve the phase shifting. We introduced a double inlet design which improved the phase shift slightly at the expense of causing significant flow instability. Another attempt was made by reducing the volume of the buffer tube element by inserting a G-10 sleeve into the tube. This did significantly improve the phase shift at the expense of increasing the volumetric displacement within the tube, thus destroying the stratified temperature gradient. As shown in Figure 7. However by introducing a form of active phase shifting at the warm end of the buffer tube by means of an additional linear motor we were able to achieve considerably better

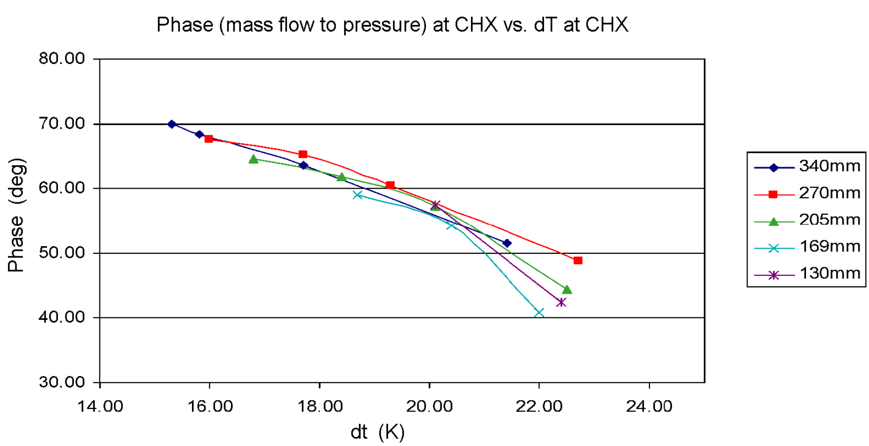

Figure 6. Phase shift between pressure and mass flow at the entrance to the WHX as a function of inerance tube length.

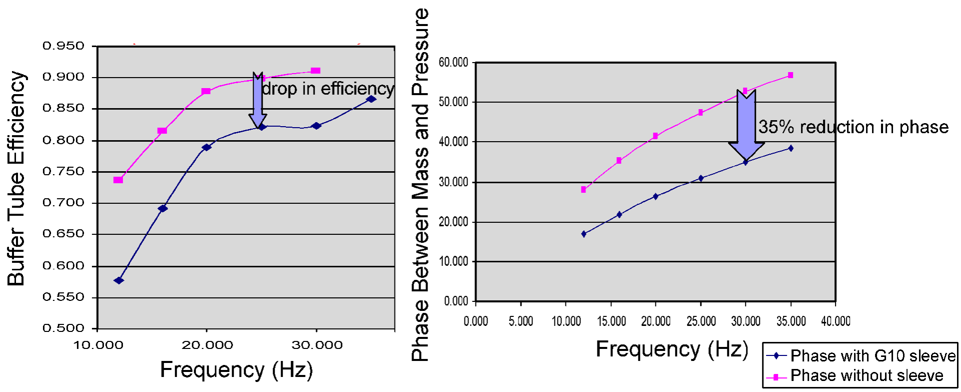

Figure 7. Increase in phase shift and decrease in efficiency as a result of inserting a G10 sleeve with a 0.106" into buffer tube.

CONCLUSION

At the optimal operating parameters, determined to be a fill pressure of 800 kPa and a pressure ratio of 1.4 at the warm end of the cold stage pulse tube at an operating frequency of 16 Hz, the test apparatus using He-4 achieved a low temperature of 6.1 K. When He-3 was substituted for the He-4 at the same operating conditions, a low temperature of 5.2 K was achieved. No noticeable improvements were gained by further modifying the operating conditions. This lower temperature, though appreciably less than with He-4, was considerably more than the 4.2 K temperature predicted by REGEN3.3. There are some possible phenomena which might cause such a discrepancy such as impurities in the employed He-3 fluid but as of yet there is no concrete justification for such a hypothesis. Continued work is now being conducted to investigate this inconsistency and try to determine its cause.

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